RESEARCH ARTICLE

Reconstructing cold climate paleoenvironments from micromorphological analysis of relict slope deposits (Serra da Estrela, Central Portugal)

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Abstract

The paper focuses on analysis of macro- and micromorphological characteristics of relict slope deposits in Serra da Estrela (Portugal) to understand the significance of different slope processes and paleoenvironmental settings. Micromorphology is a useful sedimentology technique allowing significant advances compared to macroscopic techniques. Results show that different processes are involved in the development of the slope deposits, reflecting different environmental conditions. The main processes responsible for the emplacement of the relict slope deposits are solifluction, debris-flow and runoff, but postdepositional changes are also present. Solifluction was identified in slope deposits between 650 and 1500 m a.s.l. The common microfeatures identified are circular arrangement of grains with a core grain, rounded vesicles, vertical grains, matrix deformations and fine-grained deposits. Slope deposits above 1300 m a.s.l. have a platy microstructure and coincide with the altitudinal range of the relict rock glaciers, indicating the elevation limit of permafrost. Below this altitude platy microstructures are less frequent. Slope deposits in north-facing slopes were affected by frost-induced processes in a seasonal frost regime, followed by a postdeposition illuvial phase. Debris-flow and runoff were identified in slope deposits between 680 and 1260 m a.s.l. The common microfeatures are oblique grains, grain dumps, and coarse and fine grain lineations, and banded microstructures were identified in runoff processes. Debris-flow deposits have a circular arrangement of grains without a core grain, identified in sediments in paraglacial and periglacial environments. The slope deposits show evidence of past periods of enhanced periglacial activity since the last glaciation until the Younger Dryas.

KEYWORDS

micromorphology, paleoenvironments, periglacial processes, sedimentology, slope deposits, slope processes

1 | INTRODUCTION

Slope deposits are sediment accumulations in a slope position or near its base, which essentially result from the action of gravity and reflect

[Correction added on 22 June 2020. In the acknowledgement section "Associação Geopark Estrela (AGE)" has been added in this version].

the influences of weathering (physical and chemical), transport (slope-wash and mass movements), rock type, and previous and current climate.^{1,2} Slope processes are characterized by their own stress field and stress heterogeneity and the resulting slope deposits are expected to be diverse macroscopically and microscopically.³ Slope deposits are found in all climatic regions and produce a limited number of similar landforms (e.g., talus deposits, cones, fans, depositional glacia or more widespread slope mantling sedimentary covers) that can result from more than one process.⁴ Studies have shown that different processes act together on the surface of the landform, so determining the mechanisms involved in each process requires careful analysis. Some processes are active only under limited specific environmental conditions (e.g., periglacial environments) and are associated with specific processes.^{3,4} As a result, they can be used in paleogeographic and paleoclimate reconstructions to better understand the landscape responses to climatic fluctuations during the Quaternary.⁴

The macroscopic characteristics of different types of slope deposits are well documented,^{4–8} whereas investigations on the associated micromorphological features are scarce.^{9,10} Consequently, there is a general recognition of the need for micromorphological classification of slope deposits.³ Micromorphology provides an insight into the identification, description, and interpretation of components, features, and fabrics in soils and sediments.^{11,12} It offers insights into various problems relating to processes involved in sedimentary environments and the processes of formation (deposition, deformation, and/or emplacement).³ Micromorphological studies of frost-affected soils and sediments have shown that many different microfeatures are cryogenic.¹³ Van Vliet-Lanoë et al.¹⁴ and Harris¹⁵ combined information from active, fossil, and experimental data to analyze microstructures caused by repeated freezing and thawing. The microstructures most frequently described in periglacial settings were platy structures and grain coatings. Combined, these microstructures were used to reconstruct the presence of segregation ice in the active layer and the process of gelifluction.³ Platy structure has been identified in other periglacial studies and related to cryoturbation,¹⁵ differential frost heave,¹⁶ and permafrost.¹⁷ Other microstructures developed under periglacial conditions have been identified using micromorphology; for example, Elliott and Worsley¹⁸ observed well-developed orientation of grains in solifluction sediments, Mol et al.¹⁹ described grain cracks in sediments due to a sudden drop in temperature, and van Vliet-Lanoë²⁰ identified granular structures in sediments affected by periglacial conditions.

The Iberian Peninsula mountains, including Serra da Estrela (Portugal), are of interest because a wide variety of periglacial deposits and landforms are present, not only at high altitude, but also as relict deposits in mid- to low-altitude environments, which show evidence of past periods of enhanced periglacial activity.²¹ The periglacial boundary shifted altitudinally, generally in response to the intensity of the cold periods during the Quaternary glaciations.²² Early studies of geomorphological processes related to cold climates in the Iberian Peninsula focused on geomorphological mapping, description, and relative dating of relict landforms and slope deposits.^{23–33} Recently, monitoring of present-day processes has increased in the Iberian Peninsula mountains,^{34–36} but only a few studies provide absolute dating of periglacial features.²¹ The

complexity of factors such as rough orography, high Holocene erosion rates and land degradation, has made it difficult to provide a chronological framework for the sedimentation, and additional geographic locations need to be investigated to allow reconstruction of the regional characteristics of Iberian periglacial paleoenvironments.²¹

Relict periglacial landforms and deposits in Portugal are found mainly in the northern and central mountains,³⁷ with evidence from glacial landforms and sediments suggesting the occurrence of several cold phases during the late Pleistocene.^{23,33,38} Although several studies exist on relict slope deposits in the Portuguese mountains,^{23–25,30,33,39–41} most lack a detailed sedimentological analysis, as well as an absolute chronological framework, limiting their application for paleoenvironmental reconstruction. Texier and Meireles,⁴² using macro- and micromorphological analyses in mid-altitude mountains in northern Portugal, did not observe frost-related structures that originated in Pleistocene cold-climate phases, contradicting previous studies.^{23,33,38} Vieira³³ highlighted the need to study slope deposits in more detail in Serra da Estrela (the highest mountain in Portugal), clarifying their genesis, exploring the possibilities of chronologically framing them, and evaluating their paleogeographic significance.

The main aim of this paper is to contribute to a better understanding of the morphogenetic significance of different types of slope deposits in Serra da Estrela. We also clarify the role of cold environment processes and their contributions to the Late Quaternary evolution of the slope environment. This study is the first using a detailed micromorphological investigation on the relict slope deposits in Serra da Estrela and one of the few in the Iberian Peninsula.

2 | STUDY AREA

Serra da Estrela is a granite mountain located in central Portugal and is part of the Iberian Central Cordillera (Figure 1). The mountain massif is roughly rectangular and elongated in a SW–NE direction, being ca. 45 km long and up to 20 km wide.⁴¹ It is limited by two steep fault scarps that constitute the boundaries of the massif with a relative relief of over 1,000 m. The upper area of Serra da Estrela includes two plateaus, divided by the NNE–SSW tectonic lineament of the Zêzere and Alforja valleys. The western plateau is the highest with an altitude of 1,400–1,993 m a.s.l., while the eastern plateau lies below 1,750 m. The altitude of the plateau at the boundary between granite and metamorphic rocks in the north is 1,200–1,400 m a.s.l.

Vieira et al.³³ studied in detail the glacial and periglacial geomorphology of Serra da Estrela. This included sedimentological analysis of glacial and fluvioglacial deposits, modeling of the glacier surfaces, and the description of several sites showing stratified slope, head, debris flow deposits and a detailed geomorphological map. They concluded that most of the western plateau area was glaciated during the Last Glacial Maximum (LGM), when a plateau icefield with several radiating valley glaciers was present, leading to a morphology dominated by glacial landforms. On the eastern plateau, only small glaciers occurred, and periglacial features have developed. In this paper we study the granite areas of the western and eastern plateaus, the Zêzere and

FIGURE 1 Location map of the study area. Penhas da Saúde (PS, 1,520 m); Covão da Malhada (CM, 1,500 m); Sítio das Pessoltas (SP, 1,300 m); Vila Belo Horizonte (VBH, 1,260 m); São Sebastião (SS, 1,010 m); Poço do inferno (PI, 1,008 m); Barroca de Água (BA, 1,000 m); Covão da Ponte (CP, 990 m); Sarzedo (SZ, 830 m); Souto do Concelho (SC, 700 m); São Gabriel (SG, 680 m); Unhais da Serra (US, 650 m) (elevation data: NASA Shuttle Radar Topography Mission)

Alforfa valleys, and the metasedimentary area of the Mondego Valley to the north of the plateaus (Figure 1). Seventeen slope outcrops located between 650 and 1520 m a.s.l were studied. General characteristics are described in Table 1, Figures 2 and 3, and details are found in the Supporting Information (Appendix S1).

Vieira³⁷ proposed a relative chronology based on geomorphological analysis of the relationships between glacier and periglacial evidence and on thermoluminescence dating indicating that the Last Maximum of the Glaciation of Serra da Estrela (LMGSE – ca. 30 ka BP) occurred before the LGM. Palynological analysis and radiocarbon ages from organic infills of glacial basins suggest that small glaciers still existed into the Late Glacial and periglacial activity occurred in the Younger Dryas.^{43,44}

3 | MATERIAL AND METHODS

The samples were collected from different slope deposits, located between 650 and 1,520 m a.s.l within and outside the maximum

glacier extent (Figures 1, 2 and Table 1). After removing overlying debris, the face of the slope deposits was excavated to provide a fresh surface for field analysis and sampling. The profiles were described macroscopically directly in the field, using criteria based on Hubbard and Glasser,⁴⁵ with a focus on general organization of deposits, characteristics of the layers, macrostructure, presence and type of bedding, grain-size, and clast morphology.

One sample (Souto do Concelho) was dated using ¹⁴C accelerator mass spectrometry (AMS) and calibrated using the CALIB 7.1 software together with the IntCal13 curve.⁴⁵ Dating was performed at the 14Chrono Centre of Queen's University Belfast.

For micromorphological analyses, 30 undisturbed and oriented samples were collected from the different facies and depths from each slope deposit using a steel Kubiena box (10 cm³). The undisturbed samples were not impregnated with resin in the field, for the purpose of transport, because the material was insufficiently indurated. Thin sections were produced and interpreted at TERRANTAR research lab, Federal University of Viçosa, Brazil. Each thin section sample was dried at 50°C and impregnated with a 1:1 crystic resin/styrene mix

TABLE 1 Site and micromorphological sample information (Dm = diamicton; M = massive; Ms = matrix-supported; C = clast supported; Fl = fine laminated; S = soil)

Site name	Sample code	Lithofacies	Coordinates	Aspect	Altitude (m)	Exposure size (height/width)	Geomorphological setting	Geology
Penhas da Saúde	PS1U2	Dm	40° 18' 34.12"N 7° 32' 50.79"W	S	1,520	PS1, 2 and 3: ranges between 0.8 and 1.46/50 m	Upper slope position close to a plateau/outside the glaciated area	Two-mica granite/medium- to coarse-grained (Covilhã granite)
	PS2U2	Dm						
	PS2U3	M						
	PS3U2	Dm						
	PS3U3	M						
	PS4U2	Ms						
PS4U5	Ms							
PS4U6	M					PS2: 1.85/20.5 m		
Covão da Malhada	CMU2	Dm	40° 24' 8.64"N 7° 34' 39.32"W	SSE	1,500	1.4/35 m	Upper slope position/outside the glaciated area	Two-mica granite/coarse-grained (Seia granite)
	CMU4	M						
Sítio das Pessoltas	SPU6	M	40° 21' 56.23"N 7° 32' 47.24"W	NW	1,300	1.9/9.7 m		
	SPU9	Ms						
Vila Belo Horizonte	VBHU2	Ms	40° 17' 1.96"N 7° 35' 28.39"W	SW	1,260	2.6/33.7 m	Midslope position/close to a gully/outside the glaciated area	Two-mica granite/fine-grained (Pedrice granite)
	VBHU4	Ms						
São Sebastião	SSU1	C	40° 23' 56.68"N 7° 33' 9.58"W	ENE	1,010	2.91/15 m		Two-mica granite/coarse-grained (Seia granite)
	SSU2	Ms						
Poço do inferno	PIU2	Ms	40° 23' 19.30"N 7° 32' 2.04"W	WNW	1,008	1.6/15 m	Midslope position/outside the glaciated area	
Barroca de Água	BAU3	M	40° 21' 59.78"N 7° 33' 15.59"W	ESE	1,000	8/25 m	Lower slope position/inside the glaciated area	
Covão da Ponte	CPU6	Ms	40° 26' 18.37"N 7° 30' 48.18"W	WNW	990	2.19/15 m	Lower slope position/outside the glaciated area	Metasediments/microconglomerates, conglomerates and metric layers of greywacke intercalated in a very thick pelitic sequence
Sarzedo	SZU2	Dm	40° 21' 29.96"N 7° 26' 5.79"W	WNW	830	2/12 m	Upper slope position/outside the glaciated area	Two-mica granite/coarse-grained (Seia granite)
Souto do Concelho	SCU2	Dm	40° 23' 31.25"N 7° 30' 29.34"W	NNW	700	2.5/9.5 m	Lower slope position/outside the glaciated area	Biotite granite/medium-grained (Manteigas granite)
	SCU3	Dm						
São Gabriel	SG1U2	Dm	40° 24' 7.12"N 7° 31' 26.73"W	NNE	680	SG1: 3/35 m	Lower slope position/close to a gully/outside the glaciated area	
	SG2U1	Ms						
	SG2U2	Fl						
	SG2U3	Dm				SG2: 7.3/38 m		
	SG2U4	S						
	SG3U1	Dm				SG3: 2/15.1 m		
Unhais da Serra	SG3U2	Dm						Two-mica granite/coarse-grained (Seia granite)
	USU4	C	40° 15' 49.10"N 7° 37' 14.32"W	WSW	650	5.6/17 m	Lower slope position/close to a gully/outside the glaciated area	

FIGURE 2 Overview of the 17 studied slope deposits. (a) Penhas da Saúde (PS1); (b) Penhas da Saúde (PS2); (c) Penhas da Saúde (PS3); (d) Penhas da Saúde (PS4); (e) Covão da Malhada (CM); (f) Sítio das Pessoltas (SP); (g) Vila Belo Horizonte (VBH); (h) São Sebastião (SS); (i) Poço do Inferno (PI); (j) Barroca de Água (BA); (k) Covão da Ponte (CP); (l) Sarzedo (SZ); (m) Souto do Concelho (SC); (n) São Gabriel (SG1); (o) São Gabriel (SG2); (p) São Gabriel (SG3); (q) Unhais da Serra (US)

FIGURE 3 Sedimentological logs from the 17 studied slope deposits in Serra da Estrela (for locations see Figure 1)

poured onto samples at atmospheric pressure. Impregnated samples were cut into blocks of 0.5 cm thickness using a diamond saw, and polished with corundum abrasives from 250 down to 600 mesh. After ultrasonic cleaning, the polished blocks were mounted onto glass slides followed by polishing and hand-finishing to produce 30- μ m-thick, 10 $\times$ 6-cm sized thin-sections. No cover slips were used to allow for further scanning electron microscope/energy dispersive spectroscopy analyses, and fine ultrapolishing using diamond powder of decreasing size (60 to 1 μ m) ensured that a flat surface was produced. Thin-sections were first examined under Zeiss polarizing microscope (OTM level) using an attached Pentax camera fitted with a Zeiss exposure meter in the Federal University of Viçosa (Brazil), and later with a Nikon Eclipse LV100POL polarizing microscope with an automatic table in the University of Warsaw (Poland). Micromorphological descriptions and terminology stems from original soil science studies and since then supplemented by terms common to structural geology³ following classifications developed by Brewer,⁴⁶ Bullock et al.¹⁰ and Stoops.⁴⁷ Particular attention was given to the type of voids, microstructures, coarse vs fine (c/f) related distribution, and specific microfeatures⁴⁷ (Figure 3). Description of the specific microfeatures followed Todisco and Bhiry,⁴⁸ Stoops et al.⁴⁹ and Linch and Dowdeswell.⁵⁰

4 | RESULTS

The text below provides macro- and micromorphological descriptions of units from all 30 samples. Detailed macroscopic descriptions of the complete slope outcrops can be found in the Supporting Information (Appendix S1). Sedimentary facies for all samples are shown in Figure 3, and the results of semiquantitative analysis with visual estimates^{48,50} of microscopic components are presented in Tables 2a and 2b.

4.1 | Macroscopic description

Samples were collected from units with distinctive sedimentary characteristics (Table 1, Figures 2 and 3): diamicton, bouldery units, stratified beds, and fine-grained sediments.

4.1.1 | Diamicton

The diamictons are matrix-supported (not often clast-supported) and are coarse or medium-grained (Figure 3). Subangular (most common) to subrounded boulders show a moderately to well-developed preferred orientation parallel to the slope inclination. Boulders with weakly developed preferred orientation parallel to the slope inclination are only observed in the São Gabriel deposit (SG1U2 and SG2U3) (Figure 3b).

4.1.2 | Bouldery units

The units composed of boulders are macroscopically heterogeneous (most common) or massive and are clast- or matrix-supported and

coarse- or medium-grained (Figure 3). However, the distribution and size of the boulders can be variable. Generally, they have a moderately or well-developed preferred orientation parallel to the slope inclination. Deformation features such as folds are observed in São Gabriel (SG3U2) and Unhais da Serra (USU4).

4.1.3 | Stratified beds

Gravel/coarse sand beds and/or coarse/fine sand beds in a normal graded-bedding are common (Figure 3). Gravel and coarse sand beds are aligned mostly horizontally and range between 30 and 100 cm in thickness. Fine sand beds are horizontally bedded and range from 10 to 30 cm. These units can extend vertically for several meters in the slope deposit (e.g., Sítio das Pessoltas, São Sebastião, Barroca de Água, and Covão da Ponte) (Figure 3).

4.1.4 | Fine-grained sediments

Fine-grained sediments were observed in the lower part of the visible section of the outcrops (Figure 3a). They are massive and lenticular segregated ice-form lenses (platy structure) and can be observed in the field in Penhas da Saúde (PS2U3, PS2U3 and PS4U6) and Covão da Malhada (CMU4) deposits. Massive units with dark-brown horizons are observed in Sítio das Pessoltas (SPU6 and SPU4) and Covão da Malhada (CMU3) (Figure 3a). Radiocarbon dating was performed for these dark-brown horizons, but the results were not relevant for the present research.

4.2 | Micromorphological description

A summary of micromorphological structures, using a semiquantitative analysis with visual estimates, is illustrated in Tables 2a and 2b. Their microfeatures are illustrated in the photomicrographs in Figure 4.

Most of the samples show more than one type of void (Table 2a). Vughs and planar voids are found throughout the samples in moderate and high abundance. Compound and complex packing voids are less frequent. The most commonly observed types of vughs are equidimensional, irregular, and star-shaped and are often found in association with perpendicular planar voids. Vughs are also frequently observed in samples with compound packing voids (Table 2a).

Samples with moderately and well-developed vughs and planar voids are associated with massive, platy, angular, subangular, and/or spongy microstructures (Table 2a). Compound packing voids are often connected with granular microstructure. Well-developed complex packing voids are associated with moderately developed compact and pellicular microstructures or with moderately developed intergrain microaggregate, bridged, and pellicular microstructures (Table 2a).

A chitonic c/f-related distribution is the most dominant distribution pattern throughout the samples, found at moderate and high abundance (Table 2b). A porphyric c/f-related distribution shows

TABLE 2a Results of semiquantitative micromorphological analyses. Classification according to Stoops (2003) and is as follows: - = absent; not observed; ● = low abundance, weakly developed; ●● = moderate abundance, moderately developed; ●●● = high abundance, well-developed. Feature relations are as illustrated in Figure 4

Sample code	Altitude (m)	Voids				Microstructures				
		Simple packing	Compound packing	Complex packing	Vughs	Planar	Vesicles	Intergrain microaggregate	Bridged	Compact
PS1U2	1,520	-	-	-	●●	●●	-	-	-	-
PS2U2	1,520	-	●●●	-	●	●	-	-	-	-
PS2U3	1,520	-	-	-	●●	●	-	-	-	-
PS3U2	1,520	-	●●●	-	●●●	●	-	-	-	-
PS3U3	1,520	-	-	-	●●●	●	-	-	-	-
PS4	1,520	-	-	-	●●●	●●	-	-	-	-
PS4U5	1,520	-	-	-	●●●	●●	-	-	-	-
PS4U6	1,520	-	-	-	●●●	●●●	-	-	-	-
CMU2	1,500	-	-	-	●●	●	-	-	-	-
CMU4	1,500	-	-	-	●	●●●	-	-	-	-
SPU6	1,300	-	●●●	-	●●	●	-	-	-	-
SPU9	1,300	-	●●●	-	●●	●	-	-	-	-
VBHU2	1,260	-	-	●●●	●	-	-	-	-	●●
VBHU4	1,260	-	-	●●●	-	-	-	-	-	●●
SSU1	1,010	-	-	-	●●●	●●	-	-	-	-
SSU2	1,010	-	-	-	●●	●●●	-	-	-	-
PIU2	1,008	-	●●	-	●●●	●	-	-	-	-
BAU3	1,000	-	-	●●●	●	-	-	-	●●	-
CPU6	990	-	-	-	●●	●●	●	-	-	-
SZU2	830	-	-	-	●●●	●●●	●	-	-	-
SCU2	700	-	●●	-	●●	-	-	-	●●	-
SCU3	700	-	●●●	-	●●	-	-	-	-	-
SG1U2	680	-	-	●●●	-	-	-	●●	●●	-
SG2U1	680	-	-	●●●	-	-	-	●●	●●	-
SG2U2	680	●●	-	●●	-	-	-	●	●●	-
SG2U3	680	-	●●	●	●●	●●	-	●●	-	-
SG2U4	680	-	●●●	-	●●	●	-	●●	-	-
SG3U1	680	-	●●	-	-	-	-	-	●●	●●
SG3U2	680	-	●●	●	-	-	-	-	●●	-
USU4	650	-	-	-	●●●	●	-	-	-	-

TABLE 2 a Results of semiquantitative micromorphological analyses. Classification according to Stoops (2003) and is as follows: - = absent, not observed; ● = low abundance, weakly developed; ●● = moderate abundance, moderately developed; ●●● = high abundance, well-developed. Feature relations are as illustrated in Figure 4

Sample code	Microstructures							
	Pellicular	Massive	Banded	Platy	Angular	Subangular	Granular	Spongy
PS1U2	-	●●●	-	●●	-	●	-	-
PS2U2	-	-	-	●	-	-	●●	-
PS2U3	-	●●●	-	●	-	●	-	●●
PS3U2	-	-	-	●	-	●●	●●	●●
PS3U3	-	●	-	●	●●●	●	-	●●
PS4	-	●	-	●●	-	●●●	-	●●
PS4U5	-	●●	-	●●	-	●●●	-	●●
PS4U6	-	●●	-	●●●	●●●	-	-	●●
CMU2	-	●●●	-	●	-	●	●●	●●
CMU4	-	●	-	●●●	●●	-	-	-
SPU6	-	●	-	●	-	●	●●●	-
SPU9	-	●	-	●	-	●	●●●	-
VBHU2	●●	-	●	-	-	-	-	-
VBHU4	●●	-	-	-	-	-	-	-
SSU1	-	-	-	●●	●●	-	●●	-
SSU2	-	-	-	●●●	●●●	-	-	-
PIU2	-	●	-	●	●	-	●●●	-
BAU3	●●	-	-	-	-	-	●	-
CPU6	-	●	●●	●●	-	●●	-	-
SZU2	-	●●●	-	●●	-	●●	-	●●●
SCU2	●●	-	-	-	-	-	●●●	-
SCU3	●●	-	-	-	-	-	●●●	-
SG1U2	●●	-	●●	-	-	-	-	-
SG2U1	●●	-	-	-	-	-	-	-
SG2U2	●	-	●●●	-	-	-	-	-
SG2U3	-	-	●	●●	-	●●	●	-
SG2U4	-	-	-	●	-	●	●●	-
SG3U1	●●	-	●	-	-	-	●●●	-
SG3U2	●●	-	●	-	-	-	●●●	-
USU4	-	●●	-	●	-	●●	-	2

TABLE 2b Results of semiquantitative micromorphological analyses. Classification according to Stoops (2003) and is as follows: - = absent, not observed; ● = low abundance, weakly developed; ●● = moderate abundance, moderately developed; ●●● = high abundance, well-developed. Feature relations are as illustrated in Figure 4

Sample code	Altitude (m)	c/f-related distribution										Specific microfeatures	
		Convex gefuric	Concave gefuric	Chitonic	Close porphyric	Single-spaced porphyric	Double-spaced porphyric	Open porphyric	Close fine enaulic	Single-spaced fine enaulic	Double-spaced fine enaulic	Circular arrangement of grains	
PS1U2	1,520	-	-	-	-	-	●●●	-	-	-	-	●●	
PS2U2	1,520	-	●●	●●	-	-	-	-	-	-	-	●●	
PS2U3	1,520	-	-	-	●●	●●●	-	-	-	-	-	●●	
PS3U2	1,520	-	-	●●	-	●●	●	-	-	-	-	●●●	
PS3U3	1,520	-	-	●●	●●●	●●	-	-	-	-	-	●●●	
PS4	1,520	-	-	●●	●●●	●●	-	-	-	-	-	●●●	
PS4U5	1,520	-	-	●●●	-	●●	-	-	-	-	-	●●	
PS4U6	1,520	-	-	●●	●●●	●●	-	-	-	-	-	●●	
CMU2	1,500	-	-	●●●	●●●	-	-	-	-	-	-	●●●	
CMU4	1,500	-	-	●●	●●●	-	-	-	-	-	-	●●	
SPU6	1,300	-	-	●●	-	●●	-	-	-	-	-	●	
SPU9	1,300	-	-	●●●	-	●●	-	-	-	-	-	●●	
VBHU2	1,260	-	●●●	●●	-	-	-	-	-	-	-	●	
VBHU4	1,260	●●●	-	●●	-	-	-	-	-	-	-	●	
SSU1	1,010	-	-	●●	-	-	●●●	-	-	-	-	●●	
SSU2	1,010	-	-	●	-	●●●	●●	-	-	-	-	●●●	
PIU2	1,008	-	-	●●●	-	-	-	-	-	-	-	●●	
BAU3	1,000	●●	-	●●	-	-	-	●●	-	-	-	●	
CPU6	990	-	-	●●	-	●●	-	-	-	-	-	●	
SZU2	830	-	-	●	●●●	-	-	-	-	-	-	●●●	
SCU2	700	●●	●	●●	-	-	-	●●	-	-	-	●	
SCU3	700	-	-	●●	-	-	-	-	●●●	-	-	●●	
SG1U2	680	-	-	●●	-	-	-	-	●●	●●	-	●	
SG2U1	680	-	-	●●	-	-	-	-	●●	●●	-	●●	
SG2U2	680	-	-	●	-	-	-	-	●●	-	●●●	-	
SG2U3	680	-	-	●	●●	-	-	-	●●	●●	-	●●●	
SG2U4	680	-	-	●	●●	-	●●	-	-	●●	-	●●	
SG3U1	680	-	-	●●	-	-	-	-	●●	●●	-	-	
SG3U2	680	-	-	●●	-	-	-	-	●●	●●	-	-	
USU4	650	-	-	●	●●	●●●	-	-	-	-	-	●●●	

TABLE 2b Results of semiquantitative micromorphological analyses. Classification according to Stoops (2003) and is as follows: - = absent, not observed; ● = low abundance, weakly developed; ●● = moderate abundance, moderately developed; ●●● = high abundance, well-developed. Feature relations are as illustrated in Figure 4

Sample code	Specific microfeatures											Crushed grains
	Rounded vesicle	Vertical grains	Oblique grains	Grain coatings	Silt caps	Grain dumps	Matrix deformations	Fine-grained deposits	Coarse-grain lineations	Fine-grain lineations	Grain alteration	
PS1U2	●	●●	●	●●	●●	-	●●	●●	-	-	●●	●
PS2U2	●●	●●●	●	●●	●●●	-	●●	-	-	-	●	●●
PS2U3	●●●	●●●	●	●●●	●●●	-	●●●	●●●	-	-	●	●●
PS3U2	●●●	●●	-	●●●	●●●	-	●●	●	-	-	●	●●
PS3U3	●●●	●●	●	●●●	●	-	●●●	●●●	-	-	●	●●
PS4	●●●	●●	●	●●●	●●●	-	●●●	●●●	-	-	●●	●●
PS4U5	●●●	●●	●	●●●	●●	-	●●	●	-	-	●●	●
PS4U6	●●	●●	●●	●●	●●	-	●	●●	-	-	●	●●
CMU2	●●●	●●	●●	●●●	●●●	-	●●●	●●	-	-	●●●	●●
CMU4	●	●●	●	●●●	●●	-	●	●	-	-	●●●	●●
SPU6	●●●	●●	●●	●●	●●●	-	●●	●	-	-	●●	●
SPU9	●●	●●●	●	●●	●●●	-	●●	●●●	-	-	●●	●
VBHU2	-	●	●●	●●●	●	●●	-	-	●●	-	●●	-
VBHU4	-	●	●●	●●	●	●●	-	●	●●	-	●●	-
SSU1	●●	●●	●	●●●	●●	-	-	●	-	-	●●	●●
SSU2	●	●●●	●	●	●	-	-	-	-	-	●●	●●
PIU2	●●	●●●	●	●●●	●●	-	●●	●	-	-	●●	●●●
BAU3	-	-	●●●	●●	-	●●	-	-	●●	-	●●●	●
CPU6	●●	-	●●●	●	●●●	-	-	-	-	-	●●●	●
SZU2	●●●	●●	●	●●	●●	●	●●●	●	●	●	●●●	●●●
SCU2	●●	●●	●●	●●●	●	●	-	-	-	-	●●●	●●
SCU3	●●	●●●	●	●●●	●	●	-	●●	●	-	●●●	●
SG1U2	-	-	●●	●●	-	●●	●	-	●●	-	●●	●
SG2U1	●	-	●●●	●●	●	●●●	-	●●	●●●	●	●●	●
SG2U2	-	-	●●●	●	●	●●	-	●	●●	●●	●●	-
SG2U3	-	●●	●●	●●	●	●●	●	●●	●●●	●●●	●●	●●●
SG2U4	●	●●●	●	●●	●	●●	●	●	●●	●●	●●	●●
SG3U1	-	●	●●●	●●	●	●●	-	-	●●●	-	●●	●
SG3U2	-	●	●●●	●●	●	●●	-	-	●●	●	●●●	●
USU4	●●●	●●	●●	●●	●	●	●●●	●●	●	-	●●	●●

FIGURE 4 Specific microfeatures of the slope deposit samples. Individual features are annotated in yellow. (a) Circular arrangement of grains with a core grain (PS4U2); (b) rounded vesicle, matrix around a clast (PS4U5); (c) grain coatings, laminated type with alternating laminae thickness, texture and color (SPU9); (d) grain coatings, layered type with alternating layers with different textures (CMU2); (e) vertical grains (a), oblique grains (b), grain coatings (c), nonlaminated type where coating appears as a homogenous body (PS4U6); (f) silt caps, coating covers the top of the grain (PS3U2); (g) grain dumps, concentration of a group of eight grains (SG2U1); (h) matrix deformations, alternating coarse- and fine-grained lineations (USU4); (i) fine-grained deposits, matrix-rich semi-circular domains (SPU9); (j) coarse grains lineations, five grains without contact in a line (SG2U4); (k) fine grain lineations, thin oriented line (SG2U3); (l) grain alterations, cross-linear pattern (SG2U2); (m) grain alterations, parallel pattern (SG2U2); (n) crushed grains, smooth fracture (SZU2); and (o) crushed grains, spheroidal fracture (PIU2)

several subtypes in more than one sample and are based on the distance between the coarser units. Moderately to well-developed close and single spaced porphyric are frequently observed in the samples collected in the Penhas da Saúde, Covão da Malhada and Sítio das Pessoltas (Table 2b). Three subtypes of enaulic distribution were distinguished based on the relative distance between the coarser grains. Close fine, single-spaced and double-spaced fine enaulic distributions are moderately abundant in the samples from São Gabriel (Table 2b). Gefuric indicates smaller units linked to larger units and bridges can be convex or concave. Convex gefuric types are moderately to well-developed and observed in VBHU4, BAU3, and SCU2 and concave gefuric is well-developed and observed in VBHU2 (Table 2b).

Most of the samples have more than one type of specific microfeature (Table 2b). Circular arrangements of grains comprise a concentric or circular pattern of grains with (Figure 4a) or without a core grain. They are a very common feature and are observed throughout the samples. Concentric arrangements of grains with a core grain are found in moderate to high abundance in samples from Penhas da Saúde, Covão da Malhada, Sítio das Pessoltas, São Sebastião, Poço do Inferno, Sarzedo, and Unhais da Serra. In the remaining sites we observed an arcuate or spiral arrangement of grains without a core grain

A rounded vesicle consists of a preferential sorting of matrix around a clast or void (Figure 4b). They are frequently observed in the same samples where circular arrangements of grains are developed around a core grain.

Vertical or near-vertical oriented grains and oblique or near-horizontal grains are also frequently observed in the samples. Vertical grains are generally found in moderately and high abundance in the same samples where the circular arrangements of grains are developed around a core grain, whereas oblique or near-horizontal grains are observed in the remaining samples.

Grain coatings consist of fine material ($<63\ \mu\text{m}$) (silt or clay) covering completely or almost entirely a grain or void (Figures 4c–e) and silt caps (or capping, Figure 4f) only cover the top of a grain. Grain coatings are observed in all samples (Table 2b). The analyses of grain coatings and silt caps show that most of the samples have more than one type. The most frequent type of coating is laminated (Figure 4c), followed by layered (Figure 4d), nonlaminated (Figure 4e) and compound layered. While the laminated type was found in all samples, layered types were more specifically observed in Penhas da Saúde, Covão da Malhada, Sítio das Pessoltas, São Sebastião, and Poço do Inferno; compound layered in samples from the first three sites; and nonlaminated in samples from Vila Belo Horizonte, Souto do Concelho, and São Gabriel.

Grain dumps are concentrations of grains in groups of more than three elements (Figure 4g) and are moderately abundant in Vila Belo Horizonte, Barroca de Água, and São Gabriel (Table 2a).

Matrix deformations are matrix-rich domains alternating between coarse- and fine-grained material arranged in bands or lineations (Figure 4h). Fine-grained deposits (Figure 4i) are matrix-rich semicircular domains observed in coarse material. Both these microfeatures are moderately to well-developed and are found in samples at Penhas da

Saúde, Covão da Malhada, Sítio das Pessoltas, and Unhais da Serra (Table 2a).

Coarse grain lineations (Figure 4j) comprise four or more grains without grain-to-grain contact in a line, and fine grain lineations (Figure 4k) include a very thin oriented line. Both microfeatures are found in moderately and high abundance, simultaneously, in samples from São Gabriel. Coarse grain lineations are moderately abundant in samples from Vila Belo Horizonte.

Grain alteration (Figure 4l, m) is moderately to well-developed in all samples (Table 2a) and most samples show more than one type of pattern.⁴⁷ Crushed or fractured grains are observed in almost all samples (Table 2b). Smooth fractures (Figure 4n) and spheroidal fractures (Figure 4o) are the two most common types of splitting found on the quartz grains.

5 | DISCUSSION

From the results of our micromorphological analysis it is possible to interpret different types of processes in the context of different environmental settings.⁵¹ (Table 3). In each of the following sections, textures/structures are grouped according to the dominant processes responsible for their formation or deposition. It is possible, in some cases, to differentiate overlain microstructural patterns in the deposits, indicating overprinted deposition events. Generally, all the samples show a varied composition of different microstructures and microfeatures, indicating that the sediments have been subject to extensive mechanical reworking.¹² This could be expected in this type of deposit as a result of the complex nature of slope processes.

5.1 | Penhas da Saúde (1,520 m) and Covão da Malhada (1,500 m)

The slope deposits from these two sites are generally characterized by a diamicton with well-developed preferred clast orientation parallel to the slope and by the presence of massive units with platy structures associated with ice segregation (Figure 3a). These macroscopic features are indicative of solifluction,^{7,8,20,52–55} a process generally related to periglacial environments.⁵⁶

Microscopically, the samples display variably shaped vughs, features which have been associated with air or water ejection under pressure or to cryoturbation stresses.⁴⁹ Cryoturbation is a dominant soil process in permafrost regions and refers to all soil movements due to frost action.⁵⁷ Although some cryoturbation may occur in areas of seasonal frost, it most commonly occurs in permafrost areas. Star-shaped vughs are also often observed, associated with blocky microstructures (angular and subangular). They are evidence of freezing in soils, especially in lower horizons (excluding PS3U3 and PS4U6, Table 2a).²⁰

Planar voids (Table 2a) are also a strong indication of frost penetration in soils, being associated with frost heave and the growth of ice lenses (platy structure).⁵⁸ Vertical or near-vertical grains (Table 2b

TABLE 3 Summary of the slope processes and cryogenic environments

Site name (sample code)	Altitude (m)	Aspect	Slope processes	Tentative cryogenic environment
Penhas da Saúde	1,520	S	Solifluction	Permafrost conditions
Covão da Malhada	1,500	SSE	Solifluction	Permafrost conditions
Sítio das Pessoltas	1,300	NW	Solifluction	Permafrost conditions
Vila Belo Horizonte	1,260	SW	Debris flow	Fluviatile-type flow conditions
São Sebastião	1,010	ENE	Solifluction	Seasonal frost conditions
Poço do inferno	1,008	WNW	Solifluction	Seasonal frost conditions
Barroca de Água	1,000	ESE	Debris flow	Paraglacial conditions
Covão da Ponte	990	WNW	Solifluction	Seasonal frost conditions
Sarzedo	830	WNW	Solifluction	Seasonal frost conditions
Souto do Concelho	700	NNW	Solifluction (primary deposition) followed by post-depositional processes	Seasonal frost conditions and fluviatile-type flow conditions
São Gabriel (SG1U2, SG2U1 and SG2U2)	680	NNE	Debris flow	Possible periglacial conditions
São Gabriel (SG2U3 and SG2U4)	680	NNE	Solifluction (primary deposition) followed by an illuvial phase	Seasonal frost conditions and warmer and humid conditions
São Gabriel (SG3U1 and SG3U2)	680	NNE	Solifluction (primary deposition) followed by postdepositional processes	Seasonal frost conditions and fluviatile-type flow conditions
Unhais da Serra	650	WSW	Solifluction	Seasonal frost conditions

and Figure 4e) can result from frost heave or frost jacking, occurring after the growth of ice lenses, especially during frost creep.⁵⁸

Macroscopically, the ice lenses occur in units related to a sudden grain size change from coarse to fine (Figure 3a) and tend to occur in the lower part of the active layer, at the contact with the permafrost table.²⁰ Microscopically, the ice lenses have various shapes depending on the pattern of ice segregation in the soil. In samples PS2U3, PS3U3, and PS4U6 they are curved upwards, possibly related to a progressively slower rate of freezing with depth in sediments that are moist but not saturated²⁰ and associated with fine sediments in solifluction sediments.⁵⁹ Samples closer to the surface display perpendicular planar voids that are related to rapid cooling.²¹

Two of the samples closer to the surface (PS2U2, PS3U2) exhibit complex packing voids and granular microstructures (Table 2a). These two microfeatures are not exclusive of frost-affected soils and can be found in surface horizons of spodic materials (e.g., complex packing voids) or vertisols (e.g., granular).⁴⁹ Nevertheless, granular microstructure is very common in frost-affected sediments having (sub)rounded aggregates and encircling fine-grained coatings. They are usually observed in the upper part of the soil (this case), which is most susceptible to multidirectional frost and to frequent freeze–thaw cycles.^{20,48} Grain coatings and cappings (Figure 4d, f) are important pedofeatures that represent past freeze and thaw.²⁰ The thickness of the coatings or cappings depends on how susceptible the fine material is to translocation. The samples exhibit layered (Figure 4d) and compound layered type of coatings/cappings, indicating strong eluviation of fine material that could result from melting of snow or ice lenses, or by fast freezing and/or under prolonged repeated freeze/thaw conditions.²⁰ The

abundant presence of fine materials is supported by well-developed chitonic–porphyric c/f-related distribution.

Rotation of (sub)rounded aggregates and consequent formation of downturned cappings along the surface are observed. They are probably the result of stresses induced at the grain/matrix interface during rotation, by solifluction, in the thaw phase when excess porewater pressures lead to a viscous downslope flow.⁴⁸ The circular arrangements of grains with a core grain (Figure 4a), rounded vesicles (Figure 4b), fine-grained deposits (Figure 4i) and matrix deformations (Figure 4h) are also strong evidence of rotation.^{8,48,50,59} They suggest disturbance and rotating movements in the matrix, occurring in response to velocity gradients within deforming sediments because of direct downward stress, probably in response to solifluction. Massive microstructures with an abundance of interconnected vughs (spongy microstructure) are observed, and although they are not exclusive of frost-affected soils, they are strongly related to mass-transported soil materials.⁴⁹

Although solifluction is not necessarily an indicator of the presence of permafrost,⁶⁰ the set of micromorphological characteristics of these deposits strongly suggest its occurrence. According to Oliva et al.⁶¹ paleopermafrost conditions in the lower latitude mountain ranges of the Iberian Peninsula occurred at 1,800 m in the Central Range (Gredos, 2,592 m; and Guadarrama, 2,430 m) and 2,500 m in the Sierra Nevada. In Serra da Estrela relict rock glaciers (1,220–1,340 m a.s.l.),³² which constitute the most frequent and reliable information on paleopermafrost occurrence in Mediterranean mountains,^{21,62} are scarce. Given the altitudinal range of the relict rock glaciers, the slope deposits from Penhas da Saúde and Covão da Malhada could have been produced under permafrost conditions.

5.2 | Sítio das Pessoltas (1,300 m), São Sebastião (1,010 m), and Covão da Ponte (990 m)

These three outcrops are identified as stratified slope deposits. They show an alternating openwork structure, matrix-supported layers, and fine and coarse beds (Figure 3a). These types of deposits have generally been attributed in the literature to periglacial processes and/or environments.⁶³ Other studies attribute them to sheet wash processes,⁶⁴ solifluction,^{7,65} dry grain flows,⁶⁶ debris flows,^{67,68} or nivo-eolian transport.⁶⁹ Sítio das Pessoltas presents a dark coloration in some units (Figure 3a) and may be ascribed to either pedogenic alteration (overprinting) or to post-sedimentation ferruginization of coarse-textured layers, without soil development. The organic enrichment of some layers testifies to reworking and implies that the slope was partially de-vegetated at the time of sediment emplacement.

Microscopically the samples display variably shaped vughs (Table 2a), but they are not interconnected (spongy microstructure not observed). Indications of soil freezing are displayed through star-shaped vughs associated with angular blocky microstructures²⁰ in São Sebastião and with subangular blocky microstructures in Covão da Ponte (Table 2a). These two outcrops also indicate more abundant planar voids than Sítio das Pessoltas. In São Sebastião the planar voids display vertical and perpendicular ice growth directions and could be related to the development of angular blocky microstructures. As the units are at the surface of the outcrop, this could relate to rapid cooling.²⁰ The planar voids from Covão da Ponte are thicker and have no apparent orientation. According to Van Vliet-Lanoë,⁵¹ the size of aggregates formed by ice lensing can increase progressively with depth, especially in sediments with larger grains, which is the case of Covão da Ponte (Metasediments, Table 1). This is due to the higher thermal conductivity, which results in a greater water supply for ice lens formation adjacent to coarser grains.

Sítio das Pessoltas displays complex packing voids and granular microstructures (Table 2a). Although, as previously mentioned, they are not exclusive to frost-affected soils, the observed microstructures indicate otherwise. With the granular microstructure, the rotation of sediment aggregates and consequent formation of downturned cap-pings are abundant, and probably result from differential frost heave and lateral displacement of the aggregates by solifluction.^{48,49} Granular aggregates can also be found in lower horizons, at the interface between two materials with different frost-susceptibilities or form in highly mobile solifluction lobes where there is temporary over-saturation of melt water.^{51,58} Circular arrangements of grains with a core grain (Figure 4a) and rounded vesicles (Figure 4b) are less abundant in these samples, as compared to the previous samples, and matrix deformations and fine-grained deposits are only observed in Sítio das Pessoltas (Table 2b). Nonetheless, these elements are thought to be associated with mechanical stresses and internal modifications in solifluction sediments.⁴⁸

According to Oliva et al.⁶¹ sediments of periglacial origin, such as stratified deposits, could have been produced under permafrost conditions in the Iberian Peninsula, namely in the highest slopes

and during the coldest stages. Permafrost conditions between 700 and 1,300 m were considered based on the presence of rock glaciers in northern mountain ranges (Cantabrian and Pyrenees mountains). Sítio das Pessoltas lies at the border of the altitudinal range of the relict rock glaciers in Serra da Estrela (1,220–1,340 m a.s.l.) and has a set of micromorphological characteristics that indicate that it could have been produced under permafrost conditions.

São Sebastião and Covão da Ponte are below the altitudinal range of the relict rock glaciers, and are on north-facing slopes. Topography in mountain areas determines different amounts of radiation in northern and southern slopes, affecting the spatial distribution and degree of activity of periglacial processes. Although these two outcrops also display a suite of micromorphological features, particularly abundant platy microstructures that can be linked to the presence of permafrost,²¹ such conditions have not been identified in lower latitude mountain ranges of the Iberian Peninsula.⁶¹

5.3 | Vila Belo Horizonte (1,260 m), Barroca de Água (1,000 m), and São Gabriel (SG1U2, SG2U1 and SG2U2: 680 m)

Samples from Vila Belo Horizonte, Barroca de Água, and São Gabriel (SG1U2 and SG2U1) were collected from units mainly consisting of different sized gravel and boulders with a weak to moderate preferred downslope orientation, in alternate silty-sandy or sandy-gravelly material in a matrix-supported arrangement. These sedimentary properties reflect mass wasting processes of debris flow type.^{42,70,71} Buried fine materials (VBHU5), paleosols (SG2U4), or laminated overland-flow (SG2U2) deposits are usually found at the foot-slopes and are associated with this type of depositional process.⁵⁵

The samples show abundant complex packing voids that are common between coarse and fine grains (our case) and, also, in the upper part of spodic horizons.⁴⁹ However, this type of horizon was not identified in the field. Microstructures in Vila Belo Horizonte are compact and pellicular, in Barroca de Água are bridged and pellicular, and the samples from São Gabriel show intergrain microaggregate, bridged and pellicular structures. These types of microstructures were identified by Texier and Meireles⁴² as fluvial-type flows probably related to initial high-energy episodes. The c/f-related distribution is gefuric-chitonic (Vila Belo Horizonte and Barroca de Água) or enaulic-chitonic (SG1U2, SG2U1 and SG2U2) and related to clay and silt infillings during decreasing flow stages or postdepositional modifications⁵⁵ (e.g., wetting and drying, freezing and thawing, bioturbation). The presence of banded microstructures in sample SG2U2 supports this observation. This microstructure shows larger grains at the bottom with progressively smaller grains toward the top and associated with a gradually waning sediment-laden current, depositing progressively finer material as the current velocity decreased.⁴²

Weakly developed circular arrangements of grains without a core grain were identified (Table 2b), except in sample SG2U2. Menzies and Zaniewski⁷² compared the micromorphological characteristics of a fresh debris flow deposit with Quaternary glacial deposits. Although microscopic similarities were identified, the main difference was the presence of a circular arrangement of grains without a core grain (grain turbate) in the Quaternary glacial deposits. The same specific microfeature was also found by Phillips⁷³ near the base of a Pleistocene debris flow and by Harris⁵⁴ in paraglacial deposits. They suggest that this type of microfeature develops in response to transitory rotational deformation associated with turbulent flow in the matrix of the sediments.

Coarse grain lineations (Figure 4j) are abundant in all samples (Table 2b). They form in response to parallel stresses during shear, because of the combination of stretching and shortening that eventually lead the grains to become aligned, which is regarded as a stress relief phenomenon.⁵⁰ Fine grain lineations (Figure 4k) were identified only in samples SG2U1 and SG2U2 (Table 2b) and form in response to parallel stresses during planar shear.^{72,73} These two types of microfeatures were identified in fresh debris flow deposits by Menzies and Zaniewski.⁷²

Fine grain coatings (Figure 4e) and grain dumps (Figure 4g) are abundant (Table 2b) and can be attributed to translocation of particles by percolation water when the deposition loses competence^{50,55} or by postdepositional processes.⁴² Van Vliet-Lanoë⁹ recognized fine grain coatings in debris flow deposits in periglacial environments and identified them as a result of liquefaction.

Oblique grains (Figure 4e) in a subhorizontal position are abundant (Table 2b) and can result from porewater moving through the sediments and the long axes of clasts and matrix particles are reoriented in the direction of the porewater pathway. Todisco and Bhiry⁴⁸ indicated that abundant subhorizontally aligned long pebbles can suggest short-distance low-energy transport, probably related to an accumulation stage of the debris flow sediments on the foot slope.

The azonal character of debris flows is well known.⁴ The environmental parameters that trigger this process (e.g., high-intensity rainfall, poorly cohesive detrital mantle and zones where runoff water can concentrate) probably coexisted throughout the Quaternary in the study area. Although some microfeatures observed in our samples are found in debris flows in periglacial and nonperiglacial environments, only one was exclusively found in frost-related settings (e.g., circular arrangement of grains without a core grain). In our samples they are not abundant (Table 2b), and hence it is not clear if this process was generated under cold environmental conditions. Barroca de Água is the only outcrop located inside the glaciated area (Figure 1), so deposition in a paraglacial environment could have been possible.

5.4 | Poço do inferno (1,008 m), Sarzedo (830 m), and Unhais da Serra (650 m)

The slope deposits from these sites are composed of units with different sized boulders (Poço do Inferno and Unhais da Serra) and a

diamicton (Sarzedo) in a silty-sandy or sandy-gravelly matrix and a well-developed preferred clast orientation parallel to the slope (Figure 2a, b). Deformation features such as folds are observed in Unhais da Serra. The macroscopic characteristics could indicate a solifluction origin, but strongly slope-oriented clast fabrics have been observed with other deposition processes⁴² (e.g., debris flows). Also, in contrast to the outcrops of Penhas da Saúde and Covão da Malhada, we did not observe massive units with lenticular segregated ice-form lenses.

Microscopically, frost-related evidence such as platy microstructures is abundant only in Sarzedo (Table 2a). Poço do Inferno has abundant granular microstructures, which are not exclusive evidence of periglacial conditions, as described previously. However, all the samples have specific microfeatures related to cryogenic processes,⁴⁸ namely a circular arrangement of grains (Figure 4a), rounded vesicles (Figure 4b), vertical grains (Figure 4e), and matrix deformations (Figure 4h). Poço do Inferno and Sarzedo provide the few samples that have a high abundance of crushed grains (Table 2b). They result from mechanical cracking, indicating increase moisture retention in a fissure with subsequent ice growth, resulting in frost shattering.^{49,74,75}

The three outcrops have a set of micromorphological features which are related to periglacial environments, but permafrost conditions are not certain, as the deposits are located below the altitudinal range of the relict rock glaciers in Serra da Estrela (1,220–1,340 m a.s.l.). Sarzedo has abundant platy microstructures, which can be linked to the presence of permafrost²¹ and could be an indication of these conditions at much lower altitudes than previously recorded in the mountains of the Iberian Peninsula Central Range.⁶¹ Poço do Inferno and Unhais da Serra, do not have abundant platy microstructures, but nonetheless have a group of microfeatures that could indicate permafrost conditions or seasonal front conditions. Unhais da Serra is the only of the three outcrops on a south-facing slope (Table 1) and periglacial evidence at such a low altitude has only been found in the Cantabrian Mountains (northern Iberian Peninsula).²¹

5.5 | Souto do concelho (700 m) and São Gabriel (SG3U1 and SG3U2: 680 m)

The samples from Souto do Concelho were collected from clast-supported diamicton with a well-developed preferred clast orientation parallel to the slope (Figure 3b). São Gabriel (SG3U1 and SG3U2) samples are from a matrix-supported diamicton with a moderately to well-developed preferred orientation parallel to the slope. Massive units with lenticular segregated ice-form lenses were not observed and deformation features such as folds were only found in SG3U2.

Microscopically, these samples have complex packing voids associated with a granular microstructure (Table 2b). As noted above, these microstructures are not exclusive to any environment. The absence of planar voids could indicate a nonfrost influence on these sediments. Bridged and pellicular microstructures (Table 2a)

are also observed, and this type of microstructure is related to fluvial-type flows.⁴² The c/f-related distribution is geric-chitonic (SCU2) or enaulic-chitonic (SCU3, SG3U1 and SG3U2) (Table 2b), related to fine material infillings during reduced flow stages or postdepositional modifications.⁵⁵

Large differences in microfeatures were found among the different samples. In Souto do Concelho, a circular arrangement of grains (Figure 4a), rounded vesicles (Figure 4b), and vertical grains (Figure 4e) are moderately abundant (Table 2b). These microfeatures are probably related to solifluction processes.⁴⁸ The buried soil in Souto do Concelho (Figure 2b) was radiocarbon-dated (¹⁴C) to 13,920 ± 70 BP. Texier and Meireles⁴² identified organic layers in the mountains of northern Portugal at similar altitudes with similar results. The age from the soil indicates a favorable phase for pedogenic processes and is concurrent with results from Van der Knaap and Van Leeuwen⁴⁴ obtained in Serra da Estrela. Climate conditions between 14,060 and 12,850 cal. a BP (Allerød) indicated an increase in temperature and precipitation and that closed treeless vegetation extended to above 1,845 m a.s.l. During this phase, between 12,850 and 11,875 a BP temperature decreased, and the climate became colder and drier (Younger Dryas) with a marked reduction in vegetation. This cold climate regime promoted a down-valley expansion of periglacial activity in the Iberian Peninsula mountains, reaching lower elevations.²¹ This stage could have influenced the development of frost-induced microfeatures during deposition in Souto do Concelho, reinforced by its north-facing position.

Microfeatures from São Gabriel (SG3U1 and SG3U2) include abundant oblique grains (Figure 4e), grain dumps (Figure 4g) and fine-grained lineations (Figure 4k) (Table 2b) and these microfeatures have been related to flow-like deposits.⁵⁵ According to these results, the depositional processes at the two sites are not definitive. They have macro- and microstructures indicating fluvial-type flows and solifluction. Postdepositional processes could have altered the original microstructures and thus complicate the analysis and dynamic interpretation. Bertran et al.⁵⁵ have shown that when such modifications are important, macroscopic evidence provides the most useful information for interpretation of slope deposits, because sedimentary structures are often preserved and can be used most effectively. Following this recommendation, the macrostructures indicate solifluction deposition, but the original micromorphological structures were altered by postdeposition processes related to fluvial-type events.

5.6 | São Gabriel (SG2U3 and SG2U4)

The sample SG2U4 was collected from a paleosol (Figure 3b) and was radiocarbon-dated (¹⁴C) to 25,260 ± 250 a BP.¹⁶ This indicates that pedogenic processes occurred during this stage. Nieuwendam⁷⁶ reconstructed a slight warming period around this age in the northern Iberian Peninsula mountains as did Texier and Meireles⁴² for northern Portugal. Sample SG2U3 was collected at the border between the paleosol and the diamicton (Figure 3b). It is a matrix-supported

diamicton with well-developed preferred clast orientation parallel to the slope. The paleosol shows a massive structure. Our microscopic analyses of the two samples showed that SG2U3 had strong soil characteristics, such as dark brown color aggregates due to organic matter.⁷⁷ This was surprising because the sample was taken from a unit where macroscopically no soil signs were found. This could indicate that the paleosol was affected by processes of in-situ reworking, erosion, transport, or post-deposition.⁷⁷

The samples have complex packing, vughs, and planar voids. Although, the planar voids are not abundant, they are a key indicator that frost action has affected these samples at some point. When repetitive freeze-thaw cycles affect a paleosol, platy microstructures can be affected by internal micro-erosion.²⁰ Subangular blocky and granular microstructures are observed. The combination of these type of voids and microstructures were also observed in the samples of Penhas da Saúde and Covão da Malhada and connected to cryogenic processes. Correspondingly, granular aggregates when observed in paleosol are often related to past permafrost or sometimes confused with crumb microstructures produced by biological activity.²⁰ Nevertheless, no traces of biological microfeatures were identified. We believe this paleosol was formed by transported soil materials (pedosediments), given the presence of packing of rounded aggregates and absence of in-situ biogenic features.⁷⁷ This is supported by the presence of clay coating fragments dispersed in the groundmass that indicated the formation of the soil was interrupted by a mass-transportation process, followed, in turn, by an illuvial phase during which silt grains were also translocated.⁷⁷

Intergrain microaggregate microstructures, and coarse grain and fine grain lineations are abundant and, as discussed previously, they are associated with surface run-off events.^{42,72} This is reinforced by the c/f-related distribution type (enaulic-chitonic) and grain dumps (Figure 4g), which are related to the translocation of particles by percolation water when surface run-off deposition loses competence^{50,55} or by postdepositional processes.⁴² These micro-scale characteristics are found in either, reworked soils or mass-transported soils.⁷⁷ This suggests that the soils were periodically destabilized by drastic climatic events.

Microstructures such as circular arrangements of grains with a core grain which indicate rotation in response to solifluction and vertical or near-vertical grains that result from frost heave are found in both samples.^{48,51,55,58,59} Therefore, this paleosol was probably affected by a combination of: (a) mass-transport, which at some point could be related to solifluction process during a glacial phase; and (b) illuvial phases, which could have occurred during a warmer period.

6 | CONCLUSIONS

This study shows that micromorphology as a technique for the analysis of sediments from relict slope deposits allows for significant advances in identifying slope processes and past environmental conditions, when compared to classical macroscopic analyses. However, it

is necessary to use several criteria such as macro- and microscopic structures and granulometry for reliable diagnosis of the studied sediments. This study has described the facies and microstructures of relict slope deposits of Serra da Estrela to understand their morphogenetic settings and compared the results with geomorphological evidence across varying altitudes, resulting in a robust interpretation of paleoenvironmental conditions.

The intensity of the frost-related microfeatures, such as platy microstructures, increases with increasing altitude, having a higher frequency in slope sediments above 1,300 m a.s.l. This agrees with the elevation range of relict rock glaciers that are an important permafrost indicator in mountain environments. Although frost-related microfeatures are found on north-facing slopes as low as 650 m a.s.l., no geomorphological evidence was found indicating that permafrost existed at elevations lower than 1,300 a.s.l. It is therefore more likely that the results derived from micro- and macro-analyses came from intensive seasonal frost rather than from the presence of permafrost at those sites.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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